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Published in:
Acustica United with Acta Acustica

Publication date:
2011

Document Version
Early version, also known as pre-print

Limitations Caused by Distortion in Room Impulse Response Measurements by Swept Sine Technique

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Summary

The significance of a room impulse response implies the requirement that its measurement should have a high level of accuracy in certain applications. One of the common problems in a measurement process is nonlinearity leading to the distortion of a room impulse response. Limitations caused by the distortion in room impulse response measurements by swept sine technique are analyzed here by the simulations and measurements.

For the investigation, both linear and exponential swept sines are used as an excitation signal. In the simulations, this signal is modified by the nonlinearity model in the time domain with or without memory. On the other hand, the distortion in measurements is achieved either by applying the nonlinearity model or by using higher excitation level and a loudspeaker with a highly nonlinear characteristic.

The results show that the most of distortion energy is located in the non-causal part of the extracted impulse response. In this way, the distortion products can be separated from the linear response. However, a part of the distortion energy remains in the causal part of room impulse response. As a consequence, in the case where distortion is present, the dynamic range of a measured response can be limited in a similar way as in maximum length sequence technique, although the saturation level (maximum dynamic range) is higher for swept sine technique. Thus, swept sine technique is also vulnerable to a certain extent to distortion that limits the quality of measured impulse response.

PACS no. 43.58.Gn, 43.55.Br

1. Introduction

Room impulse response (RIR) gives complete description of a room as a linear time invariant system [1]. Accordingly, RIR represents the most important characteristic in room acoustics. Therefore, measurement of a RIR has gained great significance. Many different methods and techniques have been developed for that purpose [2]. The most common techniques nowadays are swept sine [1,2,3] and maximum length sequence (MLS) [4]. Different system under test (SUT) conditions might have influence on the measurement results. Generally, there is a requirement that the SUT, including the measurement system, is LTI system [2,5]. Thus, one of the practical problems in measurement process is nonlinearity. In some measurement techniques, nonlinearity leads to appearance of distortion in RIR. For instance, in MLS technique nonlinearity causes appearance of the distortion products along the overall RIR. On the other hand, swept sine technique allows simultaneous determination of a linear RIR and distortion products, which are pulled before the linear response [1,3,6,7].

This paper investigates the influence of nonlinearity and the limitations caused by distortion in RIR measurements by swept sine technique. Analysis is carried out through the simulations and measurements. In the simulations, the general model of a system with the nonlinearity in the time domain is used [5,6,8,9,10]. The simulated nonlinearity is with and without memory. Additionally, influence of nonlinearity is analyzed in real conditions through the RIR measurements. Distortion rate in measurements is controlled by the nonlinearity model and the excitation signal level. The consequences are observed, and the results are compared.

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2. Theoretical background

2.1. Nonlinear system

Generally, a nonlinear system can be approximated to any desired precision with Volterra series

$$
\begin{aligned}
y(t) = & \int_{-\infty}^{\infty} k_1(\tau_1)\, x(t-\tau_1)\, d\tau_1 + \\
& + \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} k_2(\tau_1,\tau_2)\, x(t-\tau_1)\, x(t-\tau_2)\, d\tau_1 d\tau_2 \cdots
\end{aligned} \tag{1}
$$

where $k_i(\tau_1,\ldots,\tau_i)$ is i-th order Volterra kernel and x is the excitation signal. Given equation can explain "erroneous" behavior of the measured RIR when the SUT contains a weak nonlinearity. If SUT is a linear system, only the first order Volterra kernel is considered, while all high order kernels are equal to zero. In RIR measurements, SUT usually contains certain nonlinearities. However, in great number of instances, nonlinearities appear at the beginning of a system and they are substantially memoryless [3], Figure 1. The subsequent system is linear, and could be characterized by temporal effects, that is, memory. This situation is typical in room acoustics during the measurement of a RIR. Distortion appears in the transducer (loudspeaker), while the subsequent propagation process is essentially linear.

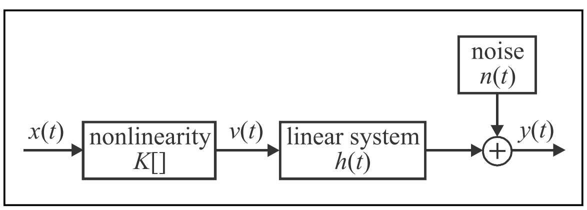

Figure 1. System consisting of initial nonlinearity and subsequent linear part

The output of memoryless nonlinearity $v(t)$ in Figure 1 can be given by

$$
\begin{aligned}
v(t) = & x(t)*k_1(t) + x^2(t)*k_2(t) + \ldots \\
& \ldots + x^N(t)*k_N(t)
\end{aligned} \tag{2}
$$

where * represents convolution. Taking into account distributive property of convolution [3], the output signal $y(t)$ (room response to the excitation signal with noise $n(t)$) becomes

$$
\begin{aligned}
y(t) = & n(t) + x(t)*k_1(t)*h(t) + \ldots \\
& \ldots + x^N(t)*k_N(t)*h(t) = \\
& = n(t) + x(t)*h_1(t) + \ldots + x^N(t)*h_N(t)
\end{aligned} \tag{3}
$$

2.2. Swept sine technique

As an attempt to overcome the requirements for linearity and time invariance, swept sine technique was developed [3]. It was pointed out that using the sine signal with varied frequency (swept sine) as an excitation, it is possible to simultaneously deconvolve the impulse response of the SUT and the distortion products.

Moreover, if excitation is the exponential sweep, the distortion products are packed at very precise anticipatory times in the non-causal part of the response (before the linear response) [2, 3]. So, a noticeable amount of distortion energy appears before linear response in the form of discrete peaks. Because of that, it is emphasized that dynamic range (SNR) of the measured response obtained by swept sine technique is higher than corresponding ones obtained by other techniques [1,3]. Furthermore, it is considered that the response obtained by swept sine technique is totally free of harmonic distortion products [1,2,3], and that its dynamic range is virtually limited only by background noise [1,2].

On the other hand, if linear sweep is used as an excitation signal, it is difficult to separate the linear impulse response from the distortion products. Then, the distortion products are stretched in time as a sort of noise [1,2,3].

3. Investigation methods

3.1. Simulations

Implementation of computer simulations enables better insight and control of distortion properties. There are different alternatives to model nonlinearity [8,9]. General lumped time domain model [8,9,10] is used here, Figure 2.

In the first step, excitation signal is filtered by low pass filter $h_f(t)$. Reason for introducing filter $h_f(t)$ in the model is comparison of results obtained by swept sine and MLS technique. This filter is important for MLS technique, because of its bipolar excitation signal. Furthermore, this is a good representation of real conditions in a RIR measurement where an excitation signal typically passes through a low pass filter of the measurement system.

After filtering, the excitation signal is distorted by application of the nonlinear element (distortion polynomial) $d\{\}$, which is for N-th order nonlinearity without memory given by

$$
d\{x_f(t)\} = A_d \left[\frac{x_f(t)}{x_{ref}}\right]^N, \tag{4}
$$

where A_d represents the amplitude of the nonlinearity and x_{ref} is the reference scaling level [9,10]. Here, different values of the nonlinearity amplitude are used, while the reference scaling level is always 1. Nonlinearity polynomial from equation 4 can be modified in such way to include a memory effects. This is done by delay of one of the arguments for certain number of samples (b). Thus, N-th order nonlinearity with memory [9] becomes

$$d\left\{x_f\left(t\right)\right\}=A_d\left[\frac{x_f\left(t\right)}{x_{ref}}\right]^{N-1}\left[\frac{x_f\left(t-b\right)}{x_{ref}}\right]. \qquad (5)$$

Afterwards, distorted signal is convolved with an impulse response of a SUT $h(r)$ (RIR).
Since background noise consisting of an electronic $n_e(t)$ and ambient noise $n(t)$ is always present in a RIR measurement, these noises can be added at appropriate places in the model, Figure 2. Finally, after adding the noise to the result of the convolution, the response signal with distortion is obtained.

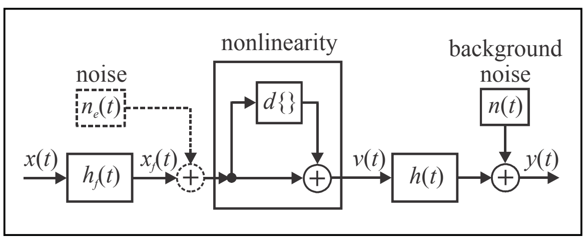

Figure 2. General lumped time domain model used for nonlinear system modeling in the simulations

RIR with the distortion is obtained after deconvolution of the response signal $y(t)$ with the inverse filter generated on the base of excitation signal. Such RIR is analyzed and compared to the corresponding RIR obtained without distortion.
In the concrete implementation of the simulation model, low pass filter $h_f(t)$ has cut-off frequency equal to half of the sampling frequency, which is f_s=44.1 kHz. For $h(t)$, both simulated and measured RIRs are used. The excitation signals (exponential and linear sweeps) are generated in the time domain with the lengths equal to the lengths of MLS signals of order 15 to 19. In this way, with the adequate amplitude equalization, it is possible to compare results obtained by swept sine and MLS technique. The nonlinearities are applied in the polynomial form, containing terms with exponents from 2 to 7.
In order to make an adequate comparison, certain quantification parameters are introduced. The difference between the distorted and undistorted RIR represents the error with following form in discrete time

$$e\left(n\right)=h_{dis}\left(n\right)-h\left(n\right). \qquad (6)$$

where n is sample number. The error $e(n)$ can contain a linear component $e_l(n)$ that is identical in shape to the linear RIR, and a nonlinear component $e_{nl}(n)$. The nonlinear error can be obtained by subtraction of the scaled linear RIR from the error [9]

$$e_{nl}\left(n\right)=e\left(n\right)-g_d h\left(n\right). \qquad (7)$$

The scaling is done with adequate gain error g_d in such a way that the nonlinear error is minimized in the root mean square sense. Now, the parameter "distortion immunity" I_d, [9,10], can be introduced as

$$I_d=10\log\left[\sum_{n=0}^{L-1}\left(h\left(n\right)\right)^2\Big/\sum_{n=0}^{L-1}\left(e_{nl}\left(n\right)\right)^2\right]. \qquad (8)$$

where L is the length of RIR.

3.2. Measurements

In the measurements, analysis of nonlinearity is more difficult due to the presence of background noise that can mask certain effects of distortion. Because of that, it is very important to find optimal parameters of the measurement.
The measurements are preformed using the measurement system based on a computer [5,7]. Exponential and linear sweep sines of the same lengths as MLS signals of orders from 16 to 19 are used for the excitation. The measurements are divided in two groups; A and B.
In the group A of the measurements, the nonlinearity is artificially introduced. The reason lies in better control of the nonlinearity parameters. Distortion is obtained by applying the nonlinear element $d\{\}$ to the excitation signals before the reproduction. Alternatively, artificial distortion is achieved by applying the mentioned nonlinearity to the recorded room response (without distortion). In the latter case, the distortion differs from those obtained by simulation and ones often met in practice. But, it is suitable for the comparison purpose.
In the measurements of group B, the nonlinearity is obtained using higher excitation levels and the loudspeaker with a highly nonlinear characteristic. Seven excitation signal levels, noted from EL1 to EL7 are used. So, the distortion rate is controlled by excitation signal level. After the measurements, the extracted RIRs are analyzed and, wherever is

possible, compared with corresponding undistorted RIRs.

4. Results

4.1. Results of simulations

When the nonlinearity is present in the model, the distortion products appear in the RIR. If the excitation is an exponential sweep and if it is long enough, the distortion products are located in the non-causal part of the RIR - prior to the linear response, i.e. before L-th sample, where L is the length of the excitation sweep. As a result of the applied nonlinearity model, the terms in the polynomial with even-order exponent cause even-order distortion products of the same and lower order. Likewise, terms with odd-order exponent results in odd-order harmonics of the same and lower order. The product of the lowest order is closest to the linear RIR. With order increasing, the distortion products are moved away from the linear part and their amplitudes are decreased.

Error sequences obtained by the simulations show that a part of distortion energy remains in the linear RIR, Figure 3. Certain distortion energy exists always in the linear RIR part independently of a tested system and the excitation signal length. When linear sweeps are used as the excitation, the distortion products are stretched throughout the RIR, but the amplitudes of the error sequences in the causal part of the RIR are similar to the corresponding ones for exponential sweeps. This implies similar distortion immunity of the linear and exponential sweeps.

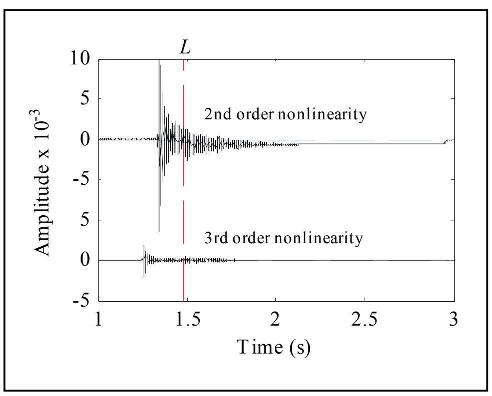

Figure 3. Error sequence $e(t)$ with second and third order nonlinearity obtained in the simulations for exponential sweep of the same length as MLS signal of order 16

The distortion immunity is calculated for various combinations of excitation sweeps and RIRs $h(t)$. A typical example is shown in Table I. The distortion immunity values are given for swept sine and MLS technique. Swept sine technique provides greater distortion immunity, and difference is increased with increase of the nonlinearity order. However, the I_d values indicate that this technique is not completely immune to the distortion.

TABLE I. Distortion immunity obtained in the simulations for MLS signal of order 16 (and the exponential sweep of the same length) and a RIR of relatively short decay

nonlin. order	I_d [dB] for MLS technique	I_d [dB] for swept sine technique
2	28.42	32.29
3	37.56	56.72
4	36.31	53.59
5	42.34	73.76
6	43.13	74.00
7	47.58	92.17

When the memory is introduced in the simulation model, length and position of the characteristic distortion parts remain very similar. Thus, the aforementioned conclusion remains the same. Regardless of the position of noise addition in the model, the outcome is increasing of overall noise, but effects differ. The addition of noise before the nonlinearity, Figure 2, leads to noisy error sequences. However, if the noise is added at the output of model, then the influence of the noise is canceled in the calculation of the nonlinear error.

4.2. Results of measurements

When the distorted excitation sweeps are used for RIR measurements (group A), and ensuring that additional distortion does not come from the measurement process (i.e. using low level excitation), the results are similar to those ones obtained by the simulations. So, the circumstances are congruent to the ones in the simulations, which imply mentioned similarity of the results. The influence of the distortion is reflected through appearance of the distortion products and additional distortion product parts. The RIRs measured with undistorted and distorted sweeps are shown in Figure 4. The additional distortion product parts exist before the L-th sample, that is, in the non-causal part, but also in the causal part of the RIR, as it is shown in the simulations. Thus, measured

RIRs with and without distortion differ in both parts.
When distorted excitation is convolved with the inverse filter, the distortion products are located at the same positions as in the measured RIR obtained with the same distorted sweep, lower curve in Figure 4. In this case, the distortion products are in the form of the discrete peaks, but there are some additional product parts especially after the second order product.
When the measured responses obtained with the undistorted sweep as excitation are distorted by the nonlinearity polynomial, similar results are obtained, except that the shapes of the distortion products and additional product parts differ to some extent from those in the previous cases.

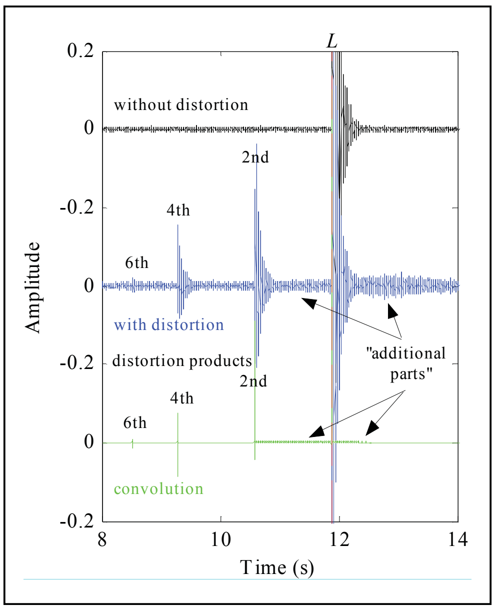

Figure 4. RIRs measured without distortion, with excitation sweep distorted by the nonlinearity polynomial of 6th order, and the result of convolution of the distorted excitation sweep with the inverse filter

In the real measurement scenario (group B), it is hard to distinguish the parts of the distortion products in the causal part of the RIR. Their presence is usually ascertained by existence of the gradual setup of the linear RIR, Figure 5, or by occurrences of certain specific shapes of the RIR that differ from the stationary structure of the background noise.
Visibility of the additional product parts can be improved by using higher excitation level and longer excitation sweep, since the background noise is reduced to certain extent while the amplitudes of the distortion products and additional product parts are increased. The gradual setup does not exist with lower excitation levels. Besides, its shape is not the same for different lengths of the excitation sweeps.

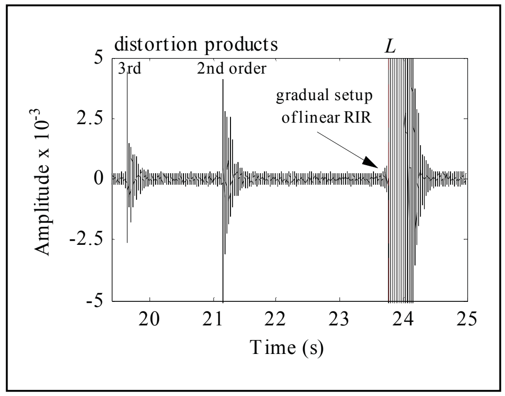

Figure 5. Zoom on the RIRs measured with the excitation sweep of the length equal to the length of MLS signal of order 19 with present nonlinearity

5. Discussion

The ability of swept sine technique to aggregate the distortion products in the non-causal part of the RIR (before linear response) represents well known advantage of this technique. However, it is shown here that although the most of distortion energy is located before the linear RIR, a certain error remains in the causal part of the RIR reducing the distortion immunity.
Comparing the distortion immunities of MLS and swept sine techniques from the simulations, it is found that the distortion immunity of swept sine technique is generally higher (with the limitation that the sweep is long enough).
Results of measurements show that increase of the excitation level (i.e. increase of the nonlinearity rate) leads to increase of amplitude of the distortion products and additional distortion product parts. One of the important consequences of this distortion product increase is the limitation of a dynamic range of the measured RIR with excitation level increase. Thus, considering only the causal part of the RIR (after L-th sample), after reaching certain excitation level, further level increase does not increase the dynamic range of the RIR, i.e. dynamic range reaches the saturation point.
This behavior can be presented by the decay curves obtained by backward integration of the measured RIRs, Figure 6. For both MLS and swept sine technique, the increase of the excitation level up to certain point results in increase of the dynamic range. However, further level increase

does not increase the dynamic range. Instead, it remains the same or becomes even smaller. This has been a known characteristic of MLS technique [10], since the initial increase of the dynamic range is caused by reduction of background noise, while certain stagnation in the dynamic range increase and subsequent decrease is caused by the increase of the distortion product level. However, a similar behavior is noticed with the decay curves of the RIRs obtained by swept sine technique. In this case, the dynamic range reaches the saturation point because of the increase of amplitude of the additional distortion product parts in the causal part of the RIR. The level of saturation point above which there is almost no further increase in the dynamic range is somewhat higher for swept sine technique, Figure 6. Generally, the difference between the saturation levels for MLS and swept sine technique can be different than in the presented case, since it depends on particular measurement conditions and existing nonlinearities. However, it is important that both techniques show a described saturation characteristic.

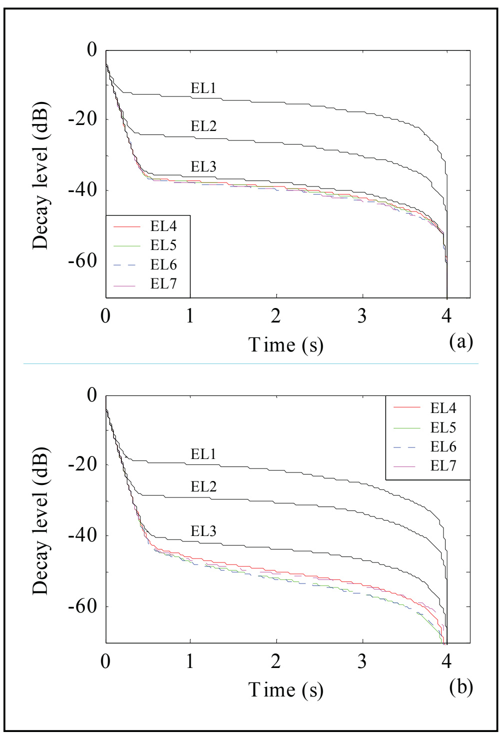

Figure 6. Decay curves of RIRs measured by MLS (a) and swept sine technique (b) using the excitation signals (MLS and exponential sweep) of the same length (the length of MLS signal of order 18) and different excitation levels in increasing order from EL1 to EL7

These results confirm that in a measurement with same conditions and the same excitation signal length, swept sine technique enables obtaining higher dynamic range of measured RIR (and decay curve) compared to MLS technique. Also, the results show that swept sine technique is not completely immune to the distortion, and that dynamic range of a RIR can be limited by the distortion.

Acknowledgement

This research is supported by the Ministry of Science and Technological Development of Serbia through the project No. 36026.

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